Synthesis of (Hemi)Carceplex Adsorbates for Self-Assembly on Gold

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The synthesis of sulfide-functionalized (hemi)carceplexes suitable for self-assembly on gold is described. A noncentrosymmetrical carceplex **9** (guest DMF) was synthesized by the combination of calix[4]arene **4** and resorcin[4]arene **3**, while a noncentrosymmetrical hemicarceplex **12** (guest NMP) was prepared by the combination of two different resorcin[4]arenes, **3** and **10**. These adsorbates form ordered self-assembled monolayers on gold with their quasi C_{4v} axis perpendicular to the surface. The two positions possible for the incarcerated guest lead to diastereotopic surfaces.

Introduction

Carcerands are molecules with an enforced hollow interior large enough to complex small guests.[1] This type of molecule can only be prepared as a complex, the so-called carceplex. The unique property of a carceplex is that the guest cannot escape from the molecular cavity without breaking covalent bonds. This class of compound has been investigated by Cram and others since 1983.[2] Carceplexes can be formed by linking two resorcin[4]arene cavitands by four spacers, with simultaneous inclusion of a solvent molecule. Until recently, only symmetrical carceplexes, i.e. the host has D_{4h} symmetry, had been investigated (vide infra).[3] Closely related to the carcerands are the hemicarcerands. These molecules also have an internal cavity, but the guest can leave the cavity without any cleavage of covalent bonds. Analogous to the carceplexes, a hemicarcerand with a complexed guest molecule is called a hemicarceplex. Hemicarceplexes differ in their structure from the carceplexes by the length and the number of spacers between the cavitands.[4] We have synthesized noncentrosymmetrical carceplexes by the combination of functionalized calix[4]arenes and resorcin[4]arenes. This type of host has C_{4v} symmetry. The incarcerated guest can adopt two different orientations, which results in a novel type of stereoisomerism (Figure 1).[5]

In a noncentrosymmetrical carceplex the guest can switch between two states by a rotation of the guest in the cavity. The energy barrier associated with this conversion depends on the structure of both the cavity and the incarcerated guest.[6] NMR experiments showed the two possible orientations for a number of guests in the carceplex, and, in addition, the energy barrier could be determined by temperature dependent measurements.[5] Various guests, such as amides (*N,N*-dimethylformamide, *N*-methyl-2-pyrrolidinone, and 1,5-dimethyl-2-pyrrolidinone), sulfoxides (DMSO, thiolane-1-oxide), 2-butanone, and 3-sulfolene, were investigated. Additionally, the size of the cavity was varied by conversion of the amide bridges into thioamide bridges. The energy barriers for the interconversion of the different diastereoisomers were as high as 17.5 kcal·mol^{-1}, which could be confirmed by molecular modeling.[5–7] In principle, these molecules are interesting as molecular switches if the molecules can be confined in space and, if the position and orientation of the guests can be determined and influenced.

It has been shown that self-assembled monolayers are attractive platforms to order and orient molecules in two dimensions.[8] We have previously developed highly-ordered self-assembled monolayers of resorcin[4]- and calix[4]arene adsorbates.[9] The area under the aromatic macrocycle filled by eight alkyl chains is crucial in the design of the adsorbates to achieve a high degree of order. This is realized via the attachment of four sulfide moieties to each macrocycle.[10] The adsorbates are bound to the gold surface by four anchoring dialkylsulfide units, filling the voids between the macrocycle and the gold surface by folding back from the interface. The match between the areas covered by the macrocycle and the alkyl chains was proven by high resolution AFM experiments.[11] Our expertise with these monolayers was used to confine the (hemi)carceplexes to a substrate and to control their relative orientation. Thus, the position of the carceplex is fixed, while the guest can still adopt different positions in the molecular cavity. In principle, two different diastereomeric surfaces can be formed, which can potentially be used for switching. In this paper, we describe the synthesis of noncentrosymmetrical carceplex adsorbates **9·DMF** and **12·DMF**. Monolayers of this new hemicarceplex adsorbate were prepared and characterized by contact angle measurements, X-ray photoelectron spectroscopy, and secondary ion mass spectrometry.

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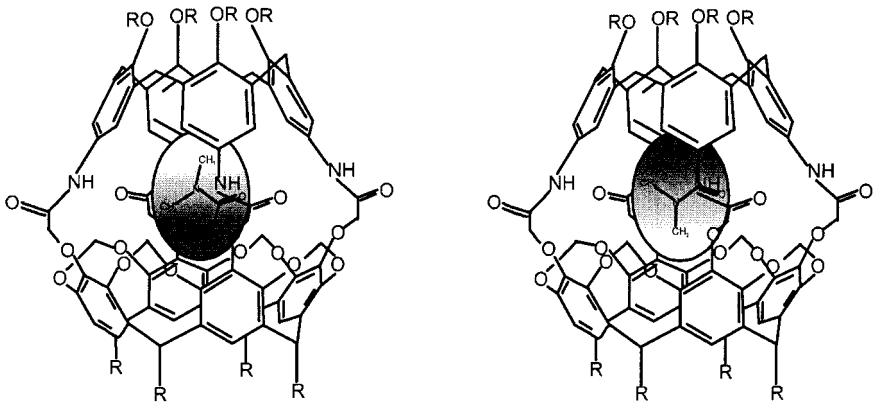


Figure 1. DMF calix[4]arene-based carceplex with two orientations of the guest

Results and Discussion[12]

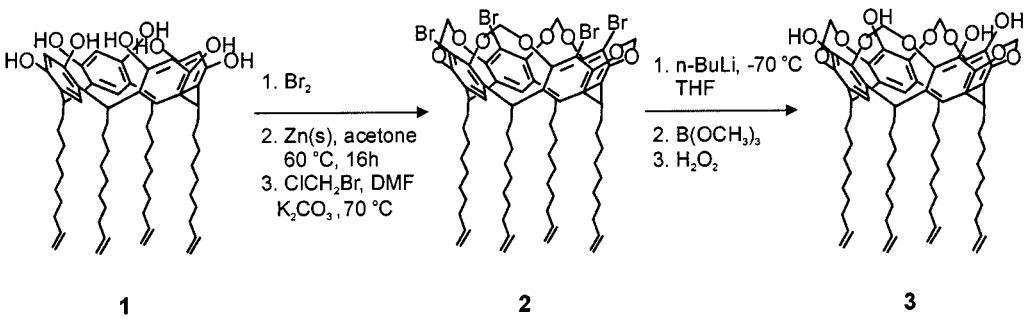
Calix[4]arene-Based Carceplex Adsorbate

The calix[4]arene-based carceplex adsorbate 9·**DMF** was synthesized according to the method of calixarene-based carceplexes, which involves the stepwise coupling of a calix[4]- and a resorcin[4]arene (cavitand) building block. [5−7] The resorcin[4]arene building block was used as a precursor to introduce the sulfur moieties to the carceplex, as previously described by us for resorcin[4]arene adsorbates.[13] Tetrol **3**, with four decylene chains required for the introduction of the sulfide, was synthesized as summarized in Scheme 1. The cyclic tetramer **1** was prepared from resorcinol and undecylenic aldehyde. Subsequent bromination of both the aromatic rings and the double bonds, selective debromination (to regenerate the double bonds), and bridging of the hydroxyl groups yielded cavitand **2**.[14] Cavitand **2** was converted in essentially quantitative yield to the tetrol **3** by bromine-lithium exchange,[15] followed by quenching with trimethylborate and oxidation with hydrogen peroxide.

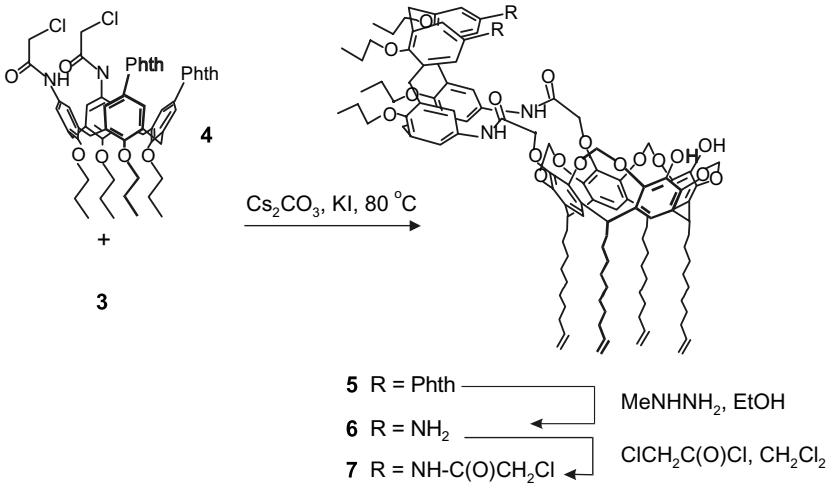
In our previous carceplex syntheses,[5−7] a 1,2-bis(chloroacetamido)-3,4-dinitrocalix[4]arene[16] was used for coupling to the resorcin[4]arene building block. However, the reduction of the nitro groups was not compatible with the presence of the double bonds in the current resorcin[4]arene building block. Instead phthalimido groups were used, which can be reduced under mild conditions to amines by various methods e.g. with hydrazine.[17] In our synthesis we employed 1,2-bis(chloroacetamido)-3,4-diphthalimidocalix[4]arene **(4)**, which we have previously described in other studies.[18]

The coupling reaction of tetrol **3** and calixarene **4** performed in MeCN at 80°C in the presence of Cs_2CO_3 and KI (Scheme 2) gave various coupling products;[19] the major isomer in the mixture was the 1:1 *endo* isomer **5**.[7] In order to convert **5** to the carceplex, the phthalimido moieties were converted into amino groups by treatment with methylhydrazine monohydrate[20] in ethanol. Subsequent selective acylation of the amino groups with chloroacetyl chloride in CH_2Cl_2 gave **7**.

The carceplex was formed quantitatively by the intramolecular alkylation of **7** in DMF at 80°C in the presence of Cs_2CO_3 and KI (Scheme 3). The resulting DMF carceplex **8·DMF** was reacted with 1-decanethiol in the presence of a catalytic amount of 9-borabicyclo[3.3.1]nonane (9-BBN) in THF, to give the tetrasulfide carceplex **9·DMF** in 64% yield. The ^{1}H NMR spectrum of **9·DMF** in $CDCl_3$ exhibits three singlets of the incarcerated DMF molecule at 4.84, 0.66, and −0.90 ppm due to the CHO and the two CH_3 groups, respectively. These signals are shifted upfield by 3.16, 2.25, and 3.69 ppm, respectively, relative to the signals of free DMF, which clearly proves that DMF is complexed inside the carcerand.[5][7] In addition, the presence of DMF was confirmed by FAB mass spectrometry which showed a distinctive peak for carceplex **9·DMF** at *m/z* 2736.9 (calcd. 2737.0).



Scheme 1. Synthesis of cavitand precursor **3**



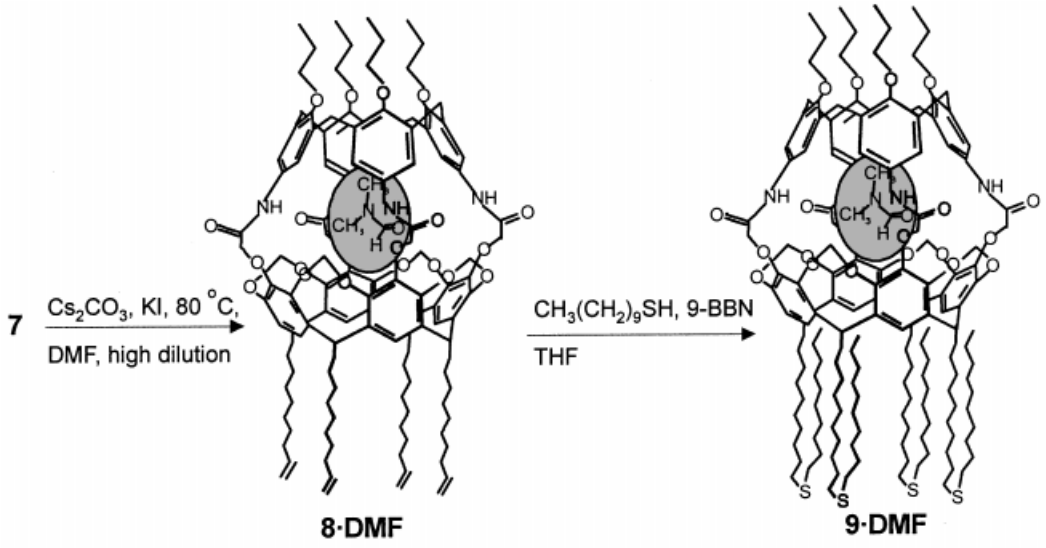
Scheme 2. Synthesis of the carceplex precursor **7**

The synthesis of this noncentrosymmetrical carceplex is based on a stepwise selective coupling of a cavitand and a calixarene. However, this route contains a large number of steps, which is further increased by the presence of the double bonds necessary for the introduction of the sulfide moieties. Therefore an alternative approach, which involved two cavitands, was also explored. Monolayer characterization of **9·DMF** showed that ordered monolayers were formed and that the C_{4v} axis of the host was perpendicular to the surface.[12]

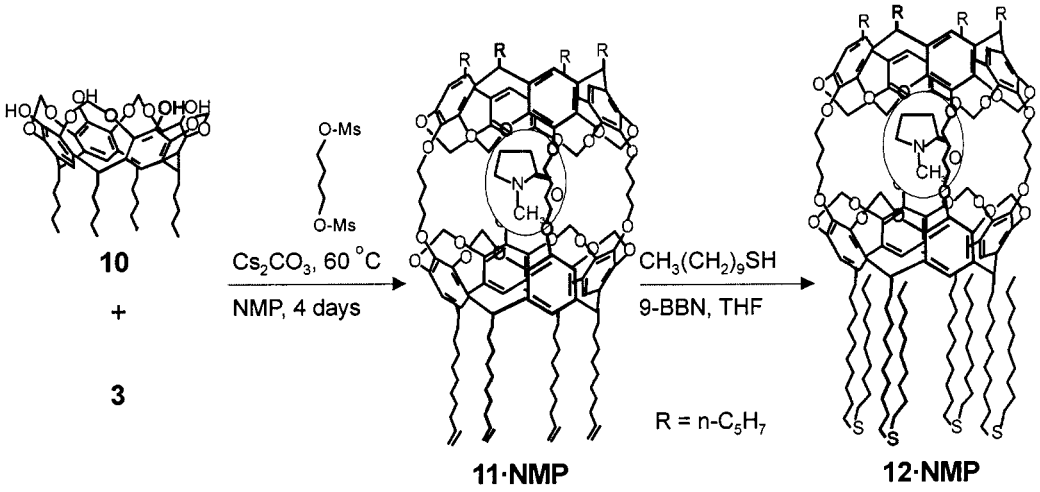
Bis(cavitand)-Based Hemicarceplex Adsorbate

Recently, a noncentrosymmetrical carceplex was reported from the direct coupling of two different cavitands.[3b] This reaction yielded a statistical mixture of the combined building blocks, which could be separated. Inspired by the intrinsic simplicity of this synthesis, we investigated modifications to this route for the preparation of a hemicarceplex adsorbate. In addition to the decreased number of synthetic steps, another advantage of a hemicarceplex is the possible exchange of the guest after the carceplex has been synthesized. This therefore permits the exchange of one guest for another which may be more suitable for the desired applications.

The synthesis of hemicarceplex **12·NMP** was adapted from the synthetic procedure described by Cram et al.[3b,21] In this approach two different resorcin[4]arene cavitands, each with four hydroxyl moieties, are linked via a spacer. For the adsorbate synthesis, a 1:1 molar mixture of known pentyl tetrol **10** and tetrol **3** were coupled in the presence of an excess of 1,4-butanediol dimesylate in NMP with Cs_2CO_3 as base. This reaction yielded a mixture of three hemicarcerands with one NMP molecule as a guest. The desired noncentrosymmetrical hemicarceplex **11** (Scheme 4) could be separated from the two symmetrical hemicarceplexes by preparative TLC and gave an overall yield of the three hemicarceplexes of 25−30%. The yield for the non-



Scheme 3. Synthesis of carceplex **9·DMF**



Scheme 4. Synthesis of hemicarceplex **12·NMP**

centrosymmetrical hemicarceplex **11·NMP** was around 5%. Fourfold addition of 1-decanethiol to the double bonds of **11·NMP** in the presence of 9-BBN afforded hemicarceplex adsorbate **12·NMP** in 70% yield. The ^{1}H NMR spectrum shows the incarcerated NMP at high field (−0.65, −0.85, and −0.94 ppm, CH_2, $C(O)CH_2$, and Me, respectively) and the FAB mass spectrum contains a peak at m/z = 3044, which corresponds to **12·NMP**.

In contrast to the calixarene-based carceplex described in the previous section, the noncentrosymmetrical hemicarcerand **12** contains a symmetrical molecular cavity. For the calixarene-based carceplexes different orientations of the guest could be determined by NMR spectroscopy.[6] However, due to rotation of the guest in **12** the chemical environment will remain unchanged and, as a result, in solution no differences in the orientation of the incarcerated guest can be determined. Surface confinement of the adsorbate will, however, result in different orientations of the guest with respect to the surface, similar to the calixarene-based carceplex **9·DMF**.

Hemicarceplex Monolayer Preparation and Characterization

Monolayers of hemicarceplex **12·NMP** were formed by the immersion of a gold substrate in a 0.1 mM solution of the adsorbate in a mixture of chloroform/ethanol (1:1, v/v), and left for 16 h at 60°C. These monolayers were prepared at 60°C, since in our experience the best monolayers are obtained when adsorbed at elevated temperatures.[13] The layers were characterized by contact angle measurements, X-ray photoelectron spectroscopy (XPS), and secondary ion mass spectrometry (SIMS).

Monolayers of hemicarceplex **12·NMP** have an advancing contact angle of 102° and a receding contact angle of 73°. Similar to monolayers of carceplex **9·DMF**, a hydrophobic surface is formed with a considerable degree of disorder in the outer part of the monolayer. The higher contact angles of **12·NMP** monolayers (102°/73°) compared to monolayers of **9·DMF** (88°/66°) are consistent with the longer alkyl chains at the outer interface (C_5 in **12·NMP** versus C_3 in **9·DMF**) and the type of binding of these alkyl chains to the (hemi)carceplex (C−C bonds in **12·NMP** versus ether bonds in **9·DMF**). These structural differences are in good agreement with the differences observed in the monolayer properties.

XPS showed the presence of carbon, sulfur, and oxygen. The relative amounts of these elements are in accord with the molecular structure. The presence of nitrogen could not be confirmed, probably due to the very small amount present in the monolayer. The S2p region was studied in more detail and showed a 2.1:1 ratio of the $S2p_{3/2}$ (centered at 161.9 eV) and $S2p_{1/2}$, which implies that all sulfides are chemically bound to the gold surface.[22] The SIMS spectra of hemicarceplex **12·NMP** monolayers revealed primarily gold/sulfur clusters. No significant peak was present for the molecular mass (M) or molecular peak plus gold (M + Au), which is consistent with the attachment of all four binding sites per molecule to the gold. The multi-attachment of these molecules to the surface reduces the probability that a high intensity molecular peak (eventually plus gold) is formed.

The combination of these techniques shows that self-assembled monolayers of the hemicarceplex can be prepared on gold surfaces. From the contact angle measurements the degree of order appears to be less than observed for other monolayers. However, the XPS measurements clearly indicate that the hemicarceplex adsorbates are bound to the gold surface with all four sulfide moieties. Therefore, it is very likely that the hemicarceplexes are oriented perpendicularly to the gold surface, similar to the previously reported carceplex adsorbates **9·DMF**.[12]

The (hemi)carceplexes described in this paper fulfill the requirement of two different orientations as well as surface confinement. The carceplexes are container molecules in which the guest may adopt two orientations (Figure 1). In principle, conversion is possible between the two states, while the associated energy barrier can be tuned by variation of the incarcerated guest.[5]

Experimental Section

General: NMR spectra were recorded with a Bruker AC250F spectrometer (^{1}H NMR 250 MHz) in $CDCl_3$. Residual solvent protons were used as internal standard and chemical shifts are given relative to tetramethylsilane (TMS). Selected ^{13}C NMR spectroscopic data are given. FAB-MS were obtained with a Finnigan MAT90 mass spectrometer using *m*-nitrobenzyl alcohol (NBA) or *o*-nitrophenyl octyl ether (NPOE) as a matrix. Elemental analyses were carried out with an 1106 Carlo-Erba element analyzer. Commercially available chemicals were purchased from Aldrich or Across Chimica. DMF was stored over molecular sieves (4Å). THF was freshly distilled from Na/benzophenone, hexane (referring to petroleum ether with b.p. 60−80°C) and CH_2Cl_2 from K_2CO_3. NaH was a 60% dispersion in mineral oil and was washed with hexane prior to use. Column chromatography was performed with silica gel 60 (Merck, particle size 0.040−0.063 mm, mesh 230−400). All reactions were carried out in an argon atmosphere.

Tetradecylene-tetrabromocavitand **(2)**,[14] 1,2-bis(chloroacetamido)-3,4-diphthalimido-tetrapropoxycalix[4]arene **(4)**,[18] and tetrapentyl-tetrahydroxycavitand **(10)**[3b] were synthesized according to literature procedures.

Tetradecylene-tetrahydroxycavitand (3): A solution of *n*-BuLi (7.9 mL, 10 mmol) in THF was added quickly to a solution of tetradecylene-tetrabromocavitand **2** (1.4 g, 1.0 mmol) in THF (150 mL) at −70°C. The mixture was stirred for 15 min and 1.7 mL (15 mmol) of $B(OCH_3)_3$ was added. The reaction mixture was allowed to warm to room temperature and was stirred for 2 h. The reaction mixture was again cooled to −70°C and a solution of H_2O_2 (15%) in 1.5 M NaOH (5.2 mL, 25 mmol) was added. The reaction mixture was allowed to warm to room temperature and stirred overnight. The excess of H_2O_2 was destroyed by the slow addition of $Na_2S_2O_5$ (2.3 g, 12 mmol) and the reaction mixture concentrated under reduced pressure. The residue was purified by column chromatography (ethyl acetate/hexane, 3:2, v/v) to give the pure tetrahydroxycavitand **3** in 40% yield (0.5 g). − ^{1}H NMR: δ = 6.63 (s, 4 H, ArH), 5.96 and 4.43 (ABq, J = 6.9 Hz, each 4 H, O−CH_2−O), 5.80−5.70 (m, 4 H, R−CH=CH_2), 5.38 (s, 4 H, OH), 5.02−4.90 (m, 8 H, Ar−CH=CH_2), 4.69 (t, J = 7.9 Hz, 4 H, RCHAr$_2$), 2.20−2.13 (m, 8 H, RCH_2−CH=CH_2), 2.09 (m, 8 H, CH_2CHAr$_2$), 1.50−1.20 (m, 48 H, CH_2). − ^{13}C NMR: δ = 139.2 (CH_2−CH=CH_2), 114.2 (C=CH_2) − MS-FAB; *m*/*z*: 1152.7 ([M$^+$] calcd. for $C_{72}H_{96}O_{12}$ 1152.7).

1:1 Coupled Product of Tetradecylene-tetrahydroxycavitand and 1,2-Bis(chloroacetamido)-3,4-diphthalimido-tetrapropoxycalix[4]arene (5): Tetrahydroxycavitand **3** (0.75 g, 0.65 mmol), Cs_2CO_3 (2.1 g, 6.5 mmol), and a catalytic amount of KI in a mixture of acetonitrile (220 mL) and THF (20 mL) was heated to reflux. A solution of calix[4]arene **4** (0.35 g, 0.33 mmol) in a mixture of acetonitrile (50 mL) and THF (10 mL) was added over 8 h and the reaction mixture was subsequently stirred under reflux for 9.5 h. After evaporation of the solvent, the residue was dissolved in dichloromethane (50 mL), washed with 1 N HCl (25 mL), H_2O (25 mL), brine (25 mL), and dried over Na_2SO_4. After concentration to dryness the crude product was purified by column chromatography (ethyl acetate/hexane, 3:2, v/v) to give pure **5** in 40% yield (1.1 g) . − ^{1}H NMR: δ = 9.82 (s, 2 H, NH), 7.8−7.6 (m, 8 H, Ar$_{pht}$H), 7.35 and 6.73 (2d, J = 2.4 Hz, 4 H, ArH), 6.94 and 6.65 (2s, 4 H, ArH), 6.9−6.8 (m, 4 H, ArH), 6.55 (d, J = 7.0 Hz, 1 H, O−CH_2−O), 6.0−5.9 (m, 3 H, O−CH_2−O), 5.8−5.7 (m, 4 H, R−CH=CH_2), 5.0−4.9 (m, 8 H, CH=CH_2), 4.8−4.5 (m, 14 H, ArCH_2Ar, O−CH_2−O, ArCHRAr, OH), 4.59 and 4.22 [ABq, J = 15.8 Hz, 4 H, O−CH_2−C(O)], 4.0−3.8 (m, 8 H, O−CH_2CH$_2$CH$_3$), 3.3−3.2 (m, 4 H, ArCH_2Ar), 2.3−2.2 [m, 8 H, CH_2(CH_2)$_7$CH=CH_2], 2.0−1.9 (m, 8 H, O−CH_2CH_2CH$_3$), 1.4−1.2 [m, 56 H, CH_2(CH_2)$_7$CH=CH_2], 1.1−1.0 (m, 12 H, O−CH_2CH$_2$CH_3). − ^{13}C NMR: δ = 167.2, 166.5 (s, C=O). − MS-FAB; *m*/*z*: 2145.3 ([M$^+$] calcd. for $C_{132}H_{152}N_4O_{22}$ 2145.1).

1:1 Coupled Product of Tetradecylene-tetrahydroxycavitand and 1,2-Bis(chloroacetamido)-3,4-diamino-tetrapropoxycalix[4]arene (6): Methylhydrazine monohydrate (0.5 mL) was added to a solution of **5** (150 mg, 70 μmol) in dichloromethane (40 mL). The reaction mixture was stirred at room temperature for 5 h. After the addition of 2 N HCl (5 mL), the mixture was stirred for another hour. The organic layer was separated, washed with H_2O (10 mL), 1 N NaOH (10 mL), H_2O (10 mL), and dried over Na_2SO_4. The solvent was evaporated under reduced pressure, and the crude diamine **6** used without further purification. − ^{1}H NMR: δ = 9.07 (s, 2 H, NH), 7.35, 6.84, 6.53, 6.49, 6.00, 5.95 (6s, 12 H, ArH), 5.9−5.7 (m, 10 H, O−CH_2−O, OH, R−CH=CH_2), 5.0−4.9 (m, 8 H, CH=CH_2), 4.8−4.1 [m, 16 H, ArCH_2Ar, O−CH_2−O, ArCHRAr, O−CH_2C(O)], 3.9−3.5 (m, 12 H, NH_2, O−CH_2CH$_2$CH$_3$), 3.2−2.8 (m, 4 H, ArCH_2Ar), 2.2−2.0 [m, 8 H, CH_2(CH_2)$_7$CH=CH_2], 2.0−1.9 (m, 8 H, O−CH_2CH_2CH$_3$), 1.4−1.2 [m, 56 H, CH_2(CH_2)$_7$CH=CH_2], 1.0−0.9 (m, 12 H, O−CH_2CH$_2$CH_3). − MS-FAB; *m*/*z*: 1884.9 ([M$^+$], calcd. for $C_{116}H_{148}N_4O_{18}$ 1885.1).

1:1 Coupled Product of Tetradecylene-tetrahydroxycavitand and 1,2-Bis(chloroacetamido)-tetrapropoxycalix[4]arene, 3,4-Bis(chloroacetamide) (7): Chloroacetyl chloride (0.5 mL. 6 mmol) was added to a solution of diamine **6** (130 mg, 70 μmol) in dichloromethane (50 mL) and the mixture stirred for 5 min. The reaction mixture was then washed with 1 N HCl (10 mL), H_2O (10 mL), 1 N NaOH (10 mL), H_2O (3 × 10 mL), and brine (10 mL), and dried over Na_2SO_4. After evaporation of the solvent, **7** was isolated in essentially quantitative yield and used without further purification. − ^{1}H NMR: δ = 9.27 [s, 2 H, NHC(O)CH$_2$−O], 7.85 [s, 2 H, NHC(O)CH$_2$Cl], 7.37 (s, 2 H, ArH), 6.94 (s, 2 H, ArH), 6.9−6.4 (m, 8 H, ArH), 6.1−5.7 (m, 8 H, O−CH_2−O, R−CH=CH_2), 5.0−4.9 (m, 8 H, CH=CH_2), 4.8−4.5 (m, 14 H, ArCH_2Ar, O−CH_2−O, ArCHRAr, OH), 4.59 and 4.22 [ABq, J = 15.8 Hz, 4 H, O−CH_2C(O)], 4.0−3.8 (m, CH_2Cl, 12 H, O−CH_2CH$_2$CH$_3$), 3.3−3.2 (m, 4 H, ArCH_2Ar), 2.2−2.1 [m, 8 H, CH_2(CH_2)$_7$CH=CH_2], 2.0−1.9 (m, 8 H, O−CH_2CH_2CH$_3$), 1.4−1.2 [m, 56 H, CH_2(CH_2)$_7$CH=CH_2], 1.1−1.0 (m, 12 H, O−CH_2CH$_2$CH_3). − MS-FAB; *m*/*z*: 2037.5 ([M$^+$], calcd. for $C_{120}H_{150}Cl_2N_4O_{20}$ 2037.0).

Tetradecylene-carceplex (8·DMF): A solution of **7** (20 mg, 10 μmol) in freshly distilled DMF (15 mL) was added dropwise over 8 h to a mixture of Cs_2CO_3 (65 mg, 0.20 mmol) and a catalytic amount of KI in distilled DMF (25 mL) at 70°C. The reaction mixture was stirred for an additional 16 h, after which it was allowed to cool to room temperature, and evaporated to dryness. The residue was dissolved in dichloromethane (10 mL), washed with 1 N HCl (10 mL), H_2O (10 mL), brine (10 mL), and dried over Na_2SO_4. Evaporation afforded **8·DMF** in essentially quantitative yield. − ^{1}H NMR: δ = 7.65 (s, 4 H, NH), 6.92 (s, 8 H, *o*-NHArH), 6.74 (s, 4 H, *m*-O−CH_2−OArH), 5.9−5.6 (m, 8 H, O−CH_2−O, CH=CH_2), 5.0−4.8 [m, 17 H, CH=CH_2, (CH_3)$_2$)NC(O)H, O−CH_2C(O)], 4.62 [t, J = 8.0 Hz, 4 H, CH(CH_2)$_8$C=CH_2], 4.40, 3.18 (ABq, J = 13.0 Hz, 8 H, ArCH_2Ar), 3.98 (part of AB, J = 7.0 Hz, 4 H, O−CH_2−O), 3.76 (t, J = 7.5 Hz, 8 H, Ar−O−CH_2CH$_2$CH$_3$), 2.3−2.2 [m, 8 H, CH_2(CH_2)$_7$CH=CH_2], 2.0−1.9 (m, 8 H, O−CH_2CH_2CH$_3$), 1.4−1.2 [m, 56 H, CH_2(CH_2)$_7$CH=CH_2], 1.1−1.0 (m, 12 H, O−CH_2CH$_2$CH_3), 0.66 (s, 3 H, DMF), −0.90 (s, 3 H, DMF). − MS-FAB; *m*/*z*: 2039.3 ([**8·DMF**$^+$], calcd. for $C_{123}H_{155}N_5O_{21}$ 2039.6), 2064.2 ([**8·DMF**$^+$ + Na]).

Tetrasulfide-carceplex (9·DMF): 1-Decanethiol (20 μL, 96 μmol) and a 0.5 M solution of 9-BBN in THF (0.2 mL, 100 μmol) were added to a solution of carceplex **8·DMF** (20 mg, 10 μmol) in THF at 0°C. The mixture was stirred for 24 h during which time it was allowed to warm to room temperature. The solvent was evaporated and the reaction mixture purified by preparative TLC (SiO_2, dichloromethane/THF, 9:1, v/v) to give **9·DMF** in 64% yield (17 mg). – ^{1}H NMR: δ = 7.65 (s, 4 H, NH), 6.92 (s, 8 H, *o*-NHAr*H*), 6.74 (s, 4 H, *m*-O–CH_2–OAr*H*), 5.76, 3.98 (ABq, *J* = 7.0 Hz, 8 H, O–CH_2–O), 4.84 [s, 1 H, $(CH_3)_2$NC(O)*H*], 4.81 [s, 8 H, O–CH_2C(O)], 4.62 [t, *J* = 8.0 Hz, 4 H, C*H*$(CH_2)_{10}$], 4.40, 3.18 (ABq, *J* = 13.0 Hz, 8 H, $ArCH_2Ar$), 3.76 (t, *J* = 7.5 Hz, 8 H, Ar–O–$CH_2CH_2CH_3$), 2.43 (t, *J* = 7.5 Hz, 16 H, CH_2–S–CH_2), 2.2–2.0 (m, 8 H, Ar–O–$CH_2CH_2CH_3$), 1.9–1.7 [m, 8 H, $CHCH_2(CH_2)_9$], 1.5–1.1 (m, 128 H, CH_2), 0.98 (t, *J* = 8.0 Hz, 12 H, Ar–O–$CH_2CH_2CH_3$), 0.82 [t, *J* = 7.5 Hz, 12 H, $(CH_2)_9CH_3$], 0.66 [s, 3 H, HC(O)$(CH_3)_2$, *trans*-CH_3], –0.90 [s, 3 H, HC(O)$(CH_3)_2$, *cis*-CH_3]. – MS-FAB; *m/z*: 2736.9 ([**9·DMF**$^+$], calcd. for $C_{163}H_{243}N_5O_{21}S_4$ 2737.0), 2586.4 ([**9·DMF**$^+$ – $CH_3(CH_2)_9S$ + Na], calcd. 2587.0).

Tetradecylene-hemicarceplex (11·NMP): Undecenyl tetrol **3** (0.60 g, 0.52 mmol) and pentyl tetrol **10** (0.46 g, 0.52 mmol), followed by 1,4-butanediol dimesylate (3.2 g, 13 mmol) were added to a mixture of Cs_2CO_3 (10 g, 31 mmol) in dried, degassed NMP (200 mL). The reaction mixture was stirred for 48 h and subsequently heated to 60°C for an additional 48 h. The solvent was evaporated under reduced pressure and the residue dissolved in chloroform and filtered through Celite. The resulting solution was concentrated and the residue loaded onto a silica gel column (dichloromethane/hexane, 7:3, v/v). Elution afforded the symmetrical hemicarceplex with two cavitands **10**, the noncentrosymmetrical **11·NMP**, and the symmetrical hemicarceplex with two cavitands **3**, respectively. The yield of **11·NMP** was 60 mg (5%). – ^{1}H NMR: δ = 6.75 (s, 8 H, ArH), 5.75 and 4.26 (ABq, *J* = 7.5 Hz, 16 H, O–CH_2–O), 5.80–5.70 (m, 4 H, R–C*H*=CH_2), 5.0–4.8 (m, 8 H, CH=CH_2), 4.65 (t, *J* = 7.8 Hz, 8 H, RC*H*Ar_2), 3.90 (s, 16 H, O–$CH_2CH_2CH_2CH_2$–O), 2.2–1.8 (m, 24 H, CH_2CHAr_2, RCH_2–CH=CH_2), 1.5–1.2 (m, 88 H, CH_2), 0.9–0.8 (m, 12 H, CH_3), –0.6- –0.7 (m, 4 H, CH_2 NMP), –0.8- –0.9 [m, 2 H, NMP, CH_2–C(O)], –0.94 (s, 3 H, NMP, N–CH_3). – MS-FAB; *m/z*: 2348 [M^+] – $C_{145}H_{193}NO_{25}$ (2347): calcd. C 74.1, H 8.3, N 0.6; found C 73.6, H 8.2, N 0.7.

Tetrasulfide-hemicarceplex (12·NMP): A solution of **11·NMP** (20 mg, 8.53 μmol) in dry THF (1 mL) was treated with 1-decanethiol (14.8 mg, 85.2 μmol) at 0°C. Solid 9-BBN (1.2 mg, 8.53 μmol) was then added to the solution. The reaction was allowed to warm to room temperature and stirred for 48 h. The solvent was removed under reduced pressure and the residue purified by preparative TLC (dichloromethane/hexane, 7:3, v/v) to afford **11·NMP** in 77% yield (20 mg). – ^{1}H NMR: δ = 6.75 (s, 8 H, ArH), 5.75 and 4.26 (ABq, *J* = 7.5 Hz, 16 H, O–CH_2–O), 4.68 (t, *J* = 7.8 Hz, 8 H, RC*H*Ar_2), 3.89 (t, 16 H, O–$CH_2CH_2CH_2CH_2$–O), 2.49 (t, *J* = 6.6 Hz, 16 H, CH_2–S–CH_2), 2.3–1.8 (m, 16 H, CH_2CHAr_2), 1.8–1.2 (m, 168 H, CH_2), 1.0–0.8 (m, 24 H, CH_3), –0.65 (m, 4 H, NMP, CH_2), –0.85 (m, 2 H, NMP, CO–CH_2), –0.94 (s, 3 H, NMP, N–CH_3). – MS-FAB; *m/z*: 3044 ([M^+], calcd. for $C_{185}H_{281}NO_{25}S_4$ 3044.9).

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